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OPTIMIZATION OF HEXAPOD LOCOMOTION USING GENETIC ALGORITHMS

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ABSTRACT
Different strategies have been adopted for the optimization of legged robots, either during their design and construction phases, or during their operation. Evolutionary strategies are a way to imitate nature replicating the process that nature designed for the generation and evolution of species. This paper presents a genetic algorithm, running over a simulation application of legged robots, that allows the optimization of several locomotion, model and controller parameters, for different locomotion speeds and gaits. Here are studied the model and locomotion parameters that optimize the robot performance, in a large range of distinct velocities.

KEY WORDS
Legged Robots, Locomotion, Gait, Optimization, Genetic Algorithms.

1 Introduction

Legged robots present significant advantages over traditional vehicles having wheels and tracks. Their major advantage is to allow locomotion in terrain inaccessible to other type of vehicles, because they do not need a continuous support surface. Several different walking robots have been developed up to now [1, 2], but in the present state of development, several aspects need to be improved and optimized. With this idea in mind, different optimization strategies have been proposed and applied to these systems, either during their design and construction phases, or during their operation, namely in what respects to the selection of the gait to be adopted and on its adaptation to the terrain and to the locomotion conditions.

Legged locomotion robots are inspired in animals observed in nature. Therefore, a frequent approach to their design and construction is to make a mechatronic mimic of the animal that is intended to replicate, either in terms of its physical dimensions, or in terms of characteristics such as the gait and the actuation of the limbs. Several examples of robots that have been developed based on this approximation are discussed by Silva and Machado [2].

Evolutionary strategies are an alternative way of imitating nature. Animals characteristics are not directly copied but, instead, is replicated the process that nature conceives for its generation and evolution.

One possibility to implement this idea makes use of genetic algorithms (GAs) as the engine to generate robot structures [3, 4, 5]. In these applications it is performed a GA modular approach to the robot design. There is a library of elementary components, such as actuated joints, links, gears, power supplies, amongst others. Several of these elements are combined to originate different structures. The generated structures are evaluated, using predefined fitness functions, and recombined among them using genetic operators. Finally, the selection process originates a robotic system that represents the best design for a specific application. These computer applications present the capability of an easy reconfiguration and application in the generation of robotic systems for distinct situations [3, 4].

There are also works in which evolutionary strategies are used to optimize the structure of a specific robot [6, 7] and to simultaneous generate the mechanical structure and the robot controller [8, 9, 10].

One important criticism that can be made to the design approach based in evolutionary strategies concerns its convergence. There is some uncertainty about achieving a solution, due to the high complexity needed for the robot to be of practical use. As an example of a work that is being implemented one can mention the robot developed by Endo and Maeno [11].

Based on these ideas, the remainder of this paper is organized as follows. Section two presents the robot model and its control architecture. Section three presents the structure of the implemented GA. Section four introduces the simulation results and their analysis. Finally, section five outlines the main conclusions of this study.

2 Hexapod Robot Model and Control Architecture

We consider a hexapod walking system (Figure 1) with $n = 6$ legs, equally distributed along both sides of the robot body, having each two rotational joints ($i.e.$, $j = \{1, 2\} \equiv \{\text{hip, knee}\}$) [12].

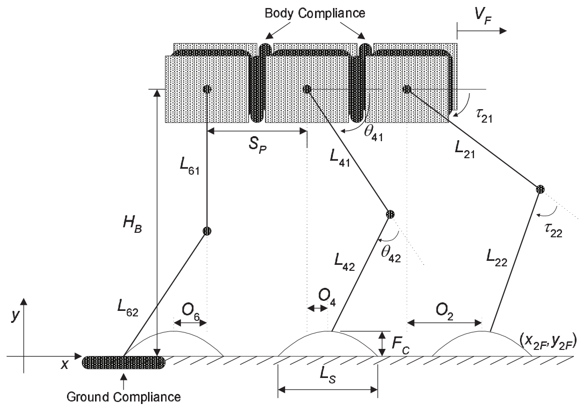

Figure 1. Kinematic and dynamic hexapod robot model

Motion is described by means of a world coordinate system. The kinematic model comprises: the cycle time T, the duty factor β, the transference time $t_T = (1-\beta)T$, the support time $t_S = \beta T$, the step length L_S, the stroke pitch S_P, the body height H_B, the maximum foot clearance F_C, the i^{th} leg lengths L_{i1} and L_{i2} (being the total length of each robot leg equal to 1 m) and the foot trajectory offset O_i ($i = 1, \ldots, n$). Moreover, we consider a periodic trajectory for each foot, with body velocity $V_F = L_S \,/\, T$.

Gaits describe sequences of leg movements, alternating between transfer and support phases. Given the particular gait and the duty factor β, it is possible to calculate, for leg i, the corresponding phase ϕ_i, the time instant where each leg leaves and returns to contact with the ground and the cartesian trajectories of the tip of the feet (that must be completed during t_T) [13]. Based on this data, the trajectory generator is responsible for producing a motion that synchronises and coordinates the legs.

The algorithm for the forward motion planning accepts, as inputs, the desired Cartesian trajectories of the leg hips $\mathbf{p_{Hd}}(t) = [x_{iHd}(t), y_{iHd}(t)]^{\mathbf{T}}$ (horizontal movement with a constant forward speed $V_F = L_S \,/\, T$) and feet $\mathbf{p_{Fd}}(t) = [x_{iFd}(t), y_{iFd}(t)]^{\mathbf{T}}$ (periodic trajectory for each foot, being the trajectory of the swing leg foot computed through a cycloid function) and, by means of an inverse kinematics algorithm ψ^{-1}, generates as outputs the joint trajectories $\mathbf{\Theta_d}(t) = [\theta_{i1d}(t), \theta_{i2d}(t)]^{\mathbf{T}}$ (selecting the solution corresponding to a forward knee), that constitute the reference for the robot control system [12].

Concerning the dynamic model, it is considered a compliant robot body, being the robot body divided in n identical segments (each with mass $M_b n^{-1}$) and a linear spring-damper system is adopted to implement the intra-body compliance (Figure 1). The contact of the i^{th} robot foot with the ground is modelled through a non-linear system with linear stiffness $K_{\eta F}$ and non-linear damping $B_{\eta F}$ ($\eta = \{x, y\}$ in the $\{$horizontal, vertical$\}$ directions, respectively) (Figure 1). The values for the parameters are based on the studies of soil mechanics (Table 1) [14].

The robot inverse dynamic model is formulated as:

Table 1
Ground parameters

Ground parameters	
K_{xF}	1.3×10^6 Nm^{-1}
K_{yF}	1.7×10^6 Nm^{-1}
B_{xF}	2.3×10^6 Nsm^{-1}
B_{yF}	2.7×10^6 Nsm^{-1}

$$\mathbf{\Gamma} = \mathbf{H}(\mathbf{\Theta})\,\ddot{\mathbf{\Theta}} + \mathbf{c}\left(\mathbf{\Theta}, \dot{\mathbf{\Theta}}\right) + \mathbf{g}(\mathbf{\Theta}) - \mathbf{F_{RH}} - \mathbf{J^T}(\mathbf{\Theta})\mathbf{F_{RF}} \tag{1}$$

where $\mathbf{\Gamma}$ is the vector of forces/torques, $\mathbf{\Theta}$ is the vector of position coordinates, $\mathbf{H}(\mathbf{\Theta})$ is the inertia matrix and $\mathbf{c}\left(\mathbf{\Theta}, \dot{\mathbf{\Theta}}\right)$ and $\mathbf{g}(\mathbf{\Theta})$ are the vectors of centrifugal/Coriolis and gravitational forces/torques, respectively. The matrix $\mathbf{J^T}(\mathbf{\Theta})$ is the transpose of the robot Jacobian matrix, $\mathbf{F_{RH}}$ is the vector of the body inter-segment forces and $\mathbf{F_{RF}}$ is the vector of the reaction forces that the ground exerts on the robot feet, being null during the foot transfer phase.

We consider that the joint actuators are not ideal, exhibiting saturation, being τ_{ijC} the controller demanded torque, τ_{ijMax} the maximum torque that the actuator can supply and τ_{ijm} the motor effective torque.

The general control architecture of the multi-legged locomotion system is presented in Figure 2 [14]. The control algorithm considers an external position and velocity feedback and an internal feedback loop with information of foot-ground interaction force. For $G_{c1}(s)$ we adopt a PD controller and for G_{c2} a simple P controller. For the PD algorithm we have:

$$G_{C1j}(s) = Kp_j + Kd_j s, \quad j = 1, 2 \tag{2}$$

being Kp_j and Kd_j the proportional and derivative gains.

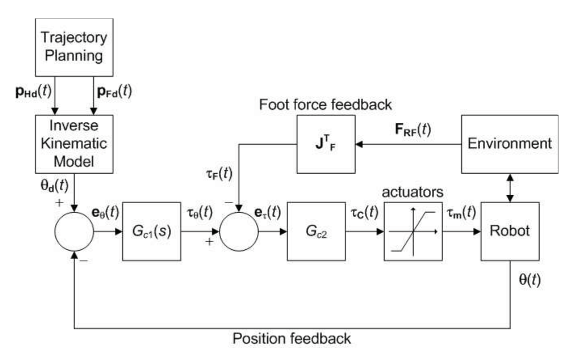

Figure 2. Quadruped robot control architecture

3 Developed Genetic Algorithm

GAs are adaptive methods which may be used to solve search and optimization problems. By mimicking the principles of natural selection, GAs are able to evolve solutions towards an optimal one. Although the optimal is not guaranteed, the GA is a stochastic search procedure that, usually, generates good results. The GA maintains a population of candidate solutions (the individuals). Individuals are evaluated and fitness values are assigned based on their relative performance. They are then given a chance to reproduce, i.e., replicating several of their characteristics. The offspring produced is modified by means of mutation and/or recombination operators before being evaluated and reinserted in the population. This is repeated until some condition is satisfied.

3.1 Measures for the Fitness Evaluation

Two global measures of the overall performance of the mechanism (in an average sense) were established. One index is inspired on the system dynamics $\{E_{av}\}$ and the other is based on the trajectory tracking errors $\{\varepsilon_{xyH}\}$ [15]. The performance optimization can be achieved through the separate minimization of each index or through the simultaneously minimization of both indices, applying a Pareto optimal front [16].

3.2 Structure of the Used Chromosome

The chromosome used in the developed GA presents 48 genes (i.e., 48 robot parameters). The genes are organized as presented in Table 2: the first gene (L_s) contains information regarding the step length and the last gene (Kd_{32}) contains the derivative gain of joint 2 of the robot rear legs. These values are coded directly into real numbers (value encoding) [17].

3.3 Base Structure of the Developed GA

The outline of the specific GA is as follows:

1. **Start:** Generate a random population of $n = 20$ ($n =$ maximum number of individuals defined by the user) suitable solutions (chromosomes). The values for the genes that constitute the chromosome, are uniformly distributed in the ranges of the admissive values [17] for the corresponding parameters.

2. **Simulation:** Simulate the robot locomotion for all chromosomes in the population using the simulation model.

3. **Fitness:** Select and evaluate the fitness function for each chromosome. The robot locomotion performance is evaluated by computing the indices $\{E_{av}\}$ and $\{\varepsilon_{xyH}\}$ [15], according to the user's selection.

Table 2
Interval of variation of the 48 genes used in the chromosome

Minimum Value	Variable	Maximum Value
$0 <$	L_s	$\leq$ 10 m
$0 <$	H_B	$\leq$ 1 m
$0 <$	β	$\leq$ 100 %
$0 <$	F_C	$\leq$ 1 m
$0 <$	L_{11}	$\leq$ 1 m
$0 <$	L_{12}	$\leq$ 1 m
$0 <$	L_{21}	$\leq$ 1 m
$0 <$	L_{22}	$\leq$ 1 m
$0 <$	L_{31}	$\leq$ 1 m
$0 <$	L_{32}	$\leq$ 1 m
$0 <$	O_1	$\leq$ 10 m
$0 <$	O_2	$\leq$ 10 m
$0 <$	O_3	$\leq$ 10 m
$0 <$	M_b	$\leq$ 100 kg
$0 <$	M_{11}	$\leq$ 10 kg
$0 <$	M_{12}	$\leq$ 10 kg
$0 <$	M_{21}	$\leq$ 10 kg
$0 <$	M_{22}	$\leq$ 10 kg
$0 <$	M_{31}	$\leq$ 10 kg
$0 <$	M_{32}	$\leq$ 10 kg
$0 <$	K_{xh}	$\leq$ 10000 Nm
$0 <$	K_{yh}	$\leq$ 10000 Nm
$0 <$	B_{xh}	$\leq$ 10000 Nms^{-1}
$0 <$	B_{yh}	$\leq$ 10000 Nms^{-1}
$-400 <$	τ_{11min}	$\leq$ 0 Nm
$0 <$	τ_{11Max}	$\leq$ 400 Nm
$-400 <$	τ_{12min}	$\leq$ 0 Nm
$0 <$	τ_{12Max}	$\leq$ 400 Nm
$-400 <$	τ_{21min}	$\leq$ 0 Nm
$0 <$	τ_{21Max}	$\leq$ 400 Nm
$-400 <$	τ_{22min}	$\leq$ 0 Nm
$0 <$	τ_{22Max}	$\leq$ 400 Nm
$-400 <$	τ_{31min}	$\leq$ 0 Nm
$0 <$	τ_{31Max}	$\leq$ 400 Nm
$-400 <$	τ_{32min}	$\leq$ 0 Nm
$0 <$	τ_{32Max}	$\leq$ 400 Nm
$0 <$	Kp_{11}	$\leq$ 10000
$0 <$	Kd_{11}	$\leq$ 1000
$0 <$	Kp_{12}	$\leq$ 10000
$0 <$	Kd_{12}	$\leq$ 1000
$0 <$	Kp_{21}	$\leq$ 10000
$0 <$	Kd_{21}	$\leq$ 1000
$0 <$	Kp_{22}	$\leq$ 10000
$0 <$	Kd_{22}	$\leq$ 1000
$0 <$	Kp_{31}	$\leq$ 10000
$0 <$	Kd_{31}	$\leq$ 1000
$0 <$	Kp_{32}	$\leq$ 10000
$0 <$	Kd_{32}	$\leq$ 1000

4. **New population:** Create a new population by repeating the following steps:

    - Selection - Select the $m = 1$ best parent chromosomes according to their fitness. These solutions are copied without changes to the new population (elitism);
    - Crossover - Select 80 % of the individuals to be replaced by the crossover of the parents: two random parents are chosen and an arithmetic mean operation is performed to produce one new offspring;
    - Mutation - Select 2 % of the individuals to be replaced by mutation of the parents: one random parent is chosen and, to selected genes of the chromosome, a small real number is added to make a new offspring;
    - Spontaneous generation - The remaining individuals are replaced by new randomly generated ones (such as in step 1).

5. **Loop:** If this iteration is the 200^{th} or the GA has converged (the value of the fitness function for the chromosome with the best fitness function is equal to the one that is in the position corresponding to 90% of the population), stop the algorithm, else, go to step 2.

4 Simulation Results and Analysis

The main objective of this study is to find the optimal values for the locomotion, robot model and controller parameters, considering that the robot is moving with variable body velocities, while adopting the Wave Gait (WG).

We test the forward straight line quadruped robot locomotion, as a function of V_F, when adopting the WG. The experiments are carried out, while considering the following values for the body velocity $V_F = \{0.1; 0.5; 1.0; 2.0; 3.0; 4.0; 5.0\}$ ms^{-1}. For each body velocity, the set of robot model, locomotion and controller parameters that simultaneously minimize both indices are determined.

The GA, with the parameters described above, and considering the simultaneously minimization of both indices (applying a Pareto optimal front [16]), lead to the results presented in the sequel.

We start by analyzing the evolution of the locomotion parameters with V_F. In a second phase, we repeat the analysis for the robot model parameters.

Figure 3 presents the evolution of the Step Length (L_S) with the forward locomotion speed (V_F). This figure shows that the optimal value of L_S must increase with V_F when considering the simultaneous minimization of these performance indices (in the perspective of the Pareto optimal front).

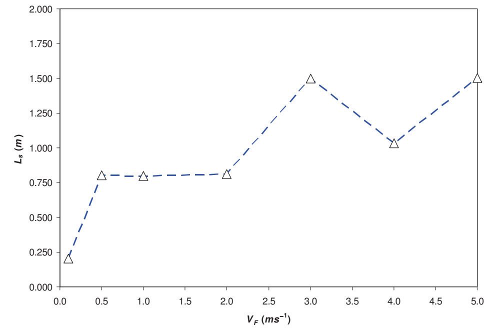

Figure 3. Evolution of the Step Length L_S with the forward locomotion speed V_F

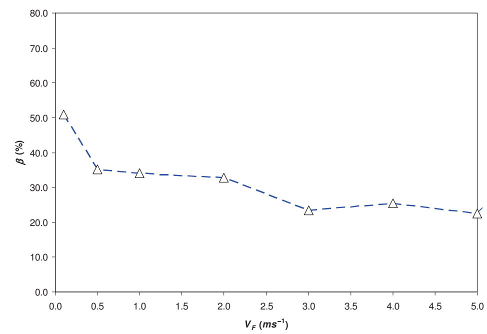

Figure 4. Evolution of the Duty Factor β with the forward locomotion speed V_F

In Figure 4 it is presented the evolution of the Duty Factor (β) with the forward locomotion speed (V_F). It is seen that the optimal value of β decreases with V_F. For V_F = 0.1 ms^{-1} the value of β is higher than 50 %, but for all other values of V_F is it lower than 50 %. This means that the robot is actually running for the values of $V_F \geq 0.5\,ms^{-1}$, considered in this study.

Figure 5 shows the evolution of the parameter Body Height (H_B) with V_F. From the analysis of the chart one can conclude that H_B remains almost constant for $V_F \leq 3.0\ ms^{-1}$ ($H_B \simeq 0.7$ m) and increases slightly for higher values of V_F under study, until it reaches $H_B \simeq 0.85$ m, for $V_F = 5.0\,ms^{-1}$.

Although not presented here, the chart that depicts the behavior of F_C with V_F, shows that F_C remains almost constant in the entire range of V_F studied, around the value $F_C \simeq 0.1\,m$.

In conclusion, regarding the locomotion parameters, we verify that they should be adapted to the walking velocity in order to optimize the robot performance. As V_F increases, the value of β should decrease and the value of L_S should increase. Regarding H_B and F_C, the first should increase for $V_F > 3.0\,ms^{-1}$ while the second should be kept constant in the vicinity of $F_C \simeq 0.1\,m$.

In the sequel we present the variation of the robot model parameters with V_F.

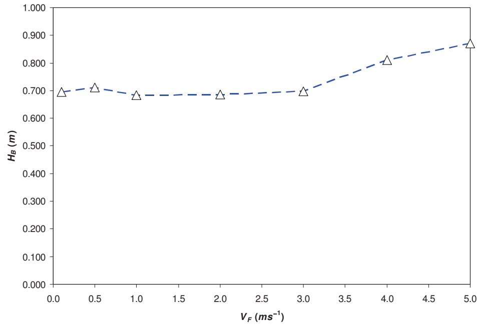

Figure 5. Evolution of the Body Height H_B with the forward locomotion speed V_F

Figure 6 shows the evolution of the optimal length of the first link of the front legs of the robot ($L_{i1},\ i\ =\ 1,\ 2$) with V_F. For low values of V_F the length of the first link is around 0.45 m and, as the velocity increases, this value decreases slightly and stays around 0.25 m. The length of the second link has the opposite behavior of the front legs of the robot, since the total length of the legs of the robot is fixed ($L_{11}\ +\ L_{12}\ =\ 1.0\,m$).

In Figure 7 it is presented the evolution of the length of the first link of the middle legs ($L_{i1},\ i\ =\ 3,\ 4$) with the forward locomotion speed (V_F). The length of L_{31} reduces for $V_F\ \leq\ 1.0\,ms^{-1}$, but stabilizes around $L_{31}\ \simeq\ 0.35\,m$ for higher values of V_F.

Figure 8 depicts the evolution of the length of the first link of the rear legs ($L_{i1},\ i\ =\ 5,\ 6$) with the forward locomotion speed (V_F). The value of L_{51} is close to 0.4 m for reduced speeds ($V_F\ \leq\ 0.5\,ms^{-1}$), decreasing slightly until reaching a value of $L_{51}\ \simeq\ 0.2\,m$ for $V_F\ \simeq\ 4.0\,ms^{-1}$. For values of $V_F\ >\ 4.0\,ms^{-1}$, L_{51} increases again until reaching $L_{51}\ =\ 0.4\,m$ for $V_F\ =\ 5.0\,ms^{-1}$.

Analyzing the lengths of the links of the robot legs, it is possible to conclude that the upper segment of the legs should be longer than the lower one, and that the relation $L_{i1}\ /\ L_{i2}$ is approximately 1/3.

In Figures 9 – 11 it is presented the evolution of the front, middle and rear feet trajectory offset ($O_i,\ i\ =\ 1,\ ...,\ n$) with V_F. The offset of the front ($O_i,\ i\ =\ 1,\ 2$) and middle ($O_i,\ i\ =\ 3,\ 4$) legs of the robot (Figures 9 and 10) shows a negative value for many values of V_F and, therefore, the robot should keep its feet backwards regarding its hips.

Finally, it is presented the evolution of the performance indices with V_F.

Figure 12 presents the evolution of the mean absolute density of energy per travelled distance (E_{av}) with V_F, on the range of V_F under consideration. It is possible to conclude that the minimum values of the index E_{av} increase with V_F.

Similarly, Figure 13 shows the evolution of the hip trajectory tracking errors (ε_{xyH}) with V_F. As in the previous case, the minimum values of ε_{xyH} also increase with V_F, in the entire rage of V_F tested.

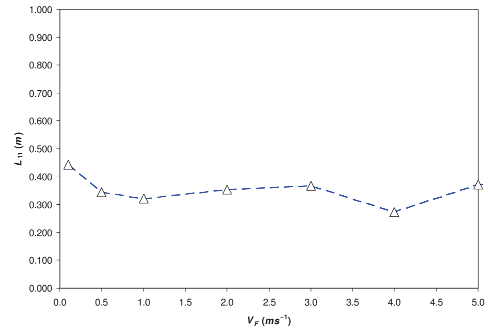

Figure 6. Evolution of the length of the first link of the front legs L_{11} with the forward locomotion speed V_F, keeping $L_{11}\ +\ L_{12}\ =\ 1.0\,m$

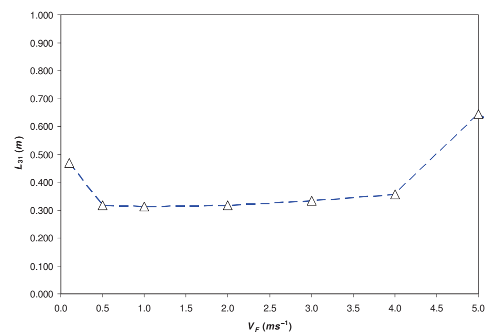

Figure 7. Evolution of the length of the first link of the middle legs L_{31} with the forward locomotion speed V_F, keeping $L_{31}\ +\ L_{32}\ =\ 1.0\,m$

5 Conclusion and Future Work

This paper describes the determination of the optimum locomotion and hexapod robot parameters, through a GA, while the robot is walking with the WG in the range $0.1\ \leq\ V_F\ \leq\ 5.0\,ms^{-1}$. The GA runs over a simulation application of legged robots (developed in the C programming language), which allows the optimization of the parameters of the robot model and gaits, for different locomotion speeds.

The results reveal that the robot model and locomotion parameters should be adapted to the walking velocity in order to optimize the robot performance. In particular, as the forward velocity increases, the values of β and H_B, should be decreased and the value of L_S increased. It was also concluded that the front, middle and rear legs should present distinct dimensions and trajectory offsets.

Based on the described GA, the authors plan to develop several simulation experiments to find the parameters that optimize the robot locomotion, from the viewpoint of the indices E_{av} and ε_{xyH}, for distinct periodic gaits, and with distinct planned trajectories of the hips, on the range of V_F under consideration on this paper.

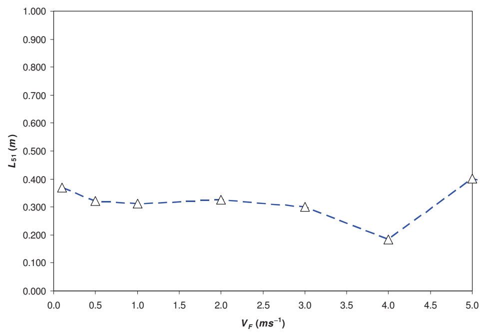

Figure 8. Evolution of the length of the first link of the rear legs L_{51} with the forward locomotion speed V_F, keeping $L_{51} + L_{52} = 1.0\,m$

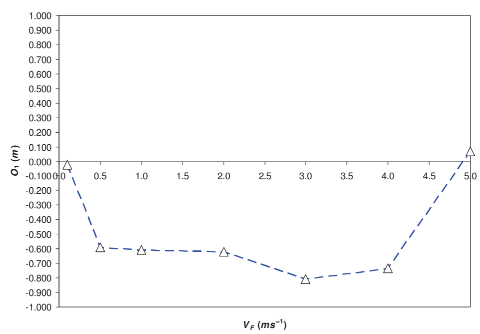

Figure 9. Evolution of the front feet trajectory offset O_1 with the forward locomotion speed V_F

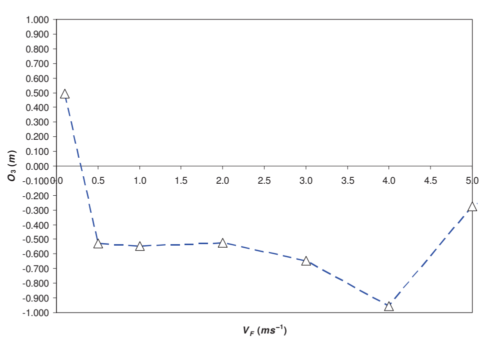

Figure 10. Evolution of the middle feet trajectory offset O_3 with the forward locomotion speed V_F

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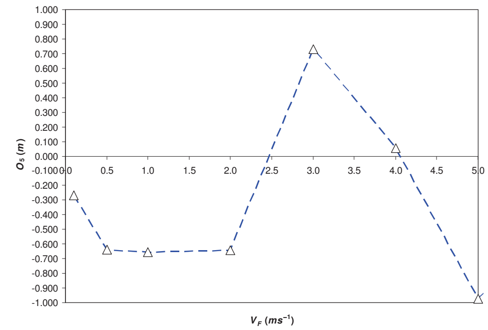

Figure 11. Evolution of the rear feet trajectory offset O_5 with the forward locomotion speed V_F

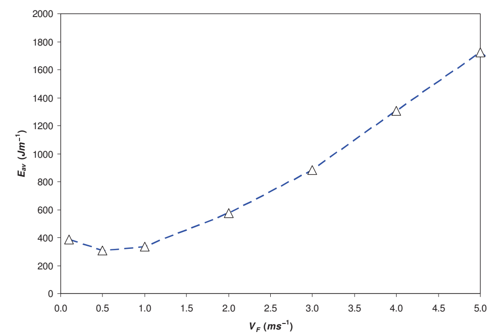

Figure 12. Evolution of the the mean absolute density of energy per travelled distance E_{av} with the forward locomotion speed V_F

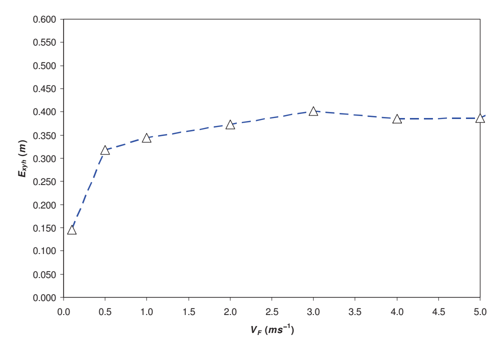

Figure 13. Evolution of the hip trajectory tracking errors ε_{xyH} with the forward locomotion speed V_F

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